

Analysis of Breakdown Phenomena in MOSFET's

ALFRED SCHÜTZ, MEMBER, IEEE, SIEGFRIED SELBERHERR, MEMBER, IEEE, AND HANS W. PÖTZL, MEMBER, IEEE

Abstract—An accurate two-dimensional self-consistent numerical model for MOS transistors which is able to predict avalanche behavior is presented. This model aims at a more principal understanding of the physical processes which arise from the avalanche effect and which eventually lead to breakdown. The system of the fundamental semiconductor equations with several generation/recombination mechanisms is solved. To improve the description of the ionization process, correction terms are introduced which account for the fact that the gate induced field does not cause ionization.

Holes which are generated in the pinch-off region by impact ionization cause a bulk current; the voltage drop at the parasitic bulk resistance initiates an internal feedback mechanism. Thus a negative resistance branch of the drain current characteristic can arise. However, at high current levels, introduced by a high gate bias and/or a short channel, this snap-back effect is often counterbalanced by strong recombination. Snap-back voltage can be estimated with this model.

LIST OF SYMBOLS AND USED CONSTANTS

A_n, A_p	Ionization coefficients for electrons (holes): 7.03×10^5 (1.52×10^6) cm^{-1} ; 1.231×10^6 (2.036×10^6) V/cm .
B_n, B_p	
C_n, C_p	Auger recombination coefficients for electrons (holes): 2.7×10^{-31} (9.9×10^{-32}) $\text{cm}^6 \text{s}^{-1}$.
d	Thickness of the substrate.
d_s	Depth of the simulation area.
D_n, D_p	Diffusion coefficients for electrons (holes).
ϵ	Dielectric permittivity.
E	Electric field.
I_B	Bulk current.
J_n, J_p	Electron (hole) current density.
L	Channel length.
$N_D^+ - N_A^-$	Effective ionized doping.
n, p	Electron (hole) density.
n_i	Intrinsic number.
n_1, p_1	Densities at recombination trap levels.

ψ	Electric potential.
q	Elementary charge.
R_{Bulk}	Parasitic bulk resistance.
s_n, s_p	Surface recombination velocities: 100 (100) cm/s .
τ_n, τ_p	Lifetime constants: 1×10^{-6} (1×10^{-6}) s .
W	Channel width.

I. INTRODUCTION

TWO-DIMENSIONAL numerical simulation of semiconductor devices has become a rapidly growing and interesting field in semiconductor physics. We have published recently a model—MINIMOS—for the two-dimensional MOS transistor analysis [1]. That model neglects majority carrier current and any generation/recombination mechanisms to simplify the computational task. Therefore, only one continuity equation has to be solved which results in reduced computing time. Although the first version of MINIMOS covers a broad area of MOS transistor simulation, there are certain applications for which modeling of the avalanche effect is essential.

Avalanche problems have so far been treated in the following manner. Firstly, Poisson's equation is solved to obtain a solution for the electrical potential distribution and then the ionization integral is evaluated by integrating the strongly field dependent ionization coefficients over the high field region. As result multiplication factors are obtained which describe the increase of current due to avalanche. Since the carrier densities need not be calculated, this method seems to be very efficient in calculating breakdown voltages. For instance, Toyabe *et al.* [2] analyzed the breakdown phenomenon in MOSFET's using this technique. In their program—CADDET—the carrier equation for one carrier type (electrons in n-channel MOSFET's and holes in p-channel MOSFET's) is solved consistently with Poisson's equation (similar to the published version of MINIMOS [1]). As CADDET makes use of the stream function technique to formulate the continuity equation [3], the avalanche generation rate cannot directly be incorporated as inhomogeneity of the continuity equation. Any feedback of the increased carrier densities on the electrical potential is, therefore, neglected.

Manuscript received July 2, 1981; revised November 18, 1981. This work was supported by the Fonds zur Förderung der Wissenschaftlichen Forschung under Project S22/11.

The authors are with Abteilung für physikalische Elektronik, Institut für Allgemeine Elektrotechnik und Elektronik, Technische Universität Wien, 1040 Vienna, Austria, and at Ludwig Boltzmann Institut für Festkörperphysik.

In contrast, the present paper deals with the consistent solution of both inhomogeneous continuity equations. Generation and recombination terms are explicitly taken into account.

In Section II the basic equations are summarized, and the ionization rates and the geometry are specified. Secondly, details of the numerical solution method are given. Then results, which are intended to demonstrate the power of our model, are presented and the underlying physical phenomena of the snap-back effect and sustain voltage are explained.

II. THE MODEL

As early as 1950 [4], van Roosbroeck had shown that the following basic semiconductor equations have to be solved to accurately analyze static carrier transport in a semiconductor device:

Poisson's equation:

$$\text{div } \epsilon \text{ grad } \psi = -q(p - n + N_D^+ - N_A^-). \quad (1)$$

Continuity equations:

$$\begin{aligned} \text{div } \vec{J}_n &= -q(G - R) \\ \text{div } \vec{J}_p &= q(G - R) \end{aligned} \quad (2)$$

with the current relations:

$$\begin{aligned} \vec{J}_n &= -q(\mu_n n \text{ grad } \psi - D_n \text{ grad } n) \\ \vec{J}_p &= -q(\mu_p p \text{ grad } \psi + D_p \text{ grad } p). \end{aligned} \quad (3)$$

The right-hand sides of (2) are the generation and recombination rates which are usually negligible in nonavalanche regions. When explicitly considering avalanche, however, electron-hole pair generation cannot be neglected any longer because avalanche breakdown is completely governed by generation. Recombination must not be neglected either because the high level of ionization in the high field regions can lead to a drastic increase of carrier densities all over the device, thus rendering recombination more important. The $(G - R)$ term of our present model contains, therefore, thermal (including surface) generation/recombination, Auger recombination, and avalanche generation:

$$(G - R) = (G - R)_{\text{th}} + (G - R)_s + (G - R)_{\text{Aug}} + G_a \quad (4)$$

with

$$(G - R)_{\text{th}} = \frac{n_i^2 - p \cdot n}{\tau_n(p + p_1) + \tau_p(n + n_1)} \quad (5a)$$

$$(G - R)_s = \frac{n_i^2 - p \cdot n}{(p + p_1)/s_n + (n + n_1)/s_p} \cdot \delta(y) \quad (5b)$$

where $\delta(y)$ is the Dirac-Delta function ($y = 0$ denotes the interface),

$$(G - R)_{\text{Aug}} = (n_i^2 - p \cdot n)(C_n n + C_p p) \quad (5c)$$

$$\begin{aligned} G_a &= \frac{|\vec{J}_n|}{q} A_n \exp\left(-\frac{B_n |\vec{J}_n|}{|\vec{E}| \cdot \vec{J}_n}\right) \\ &+ \frac{|\vec{J}_p|}{q} A_p \exp\left(-\frac{B_p |\vec{J}_p|}{|\vec{E}| \cdot \vec{J}_p}\right) \end{aligned} \quad (5d)$$

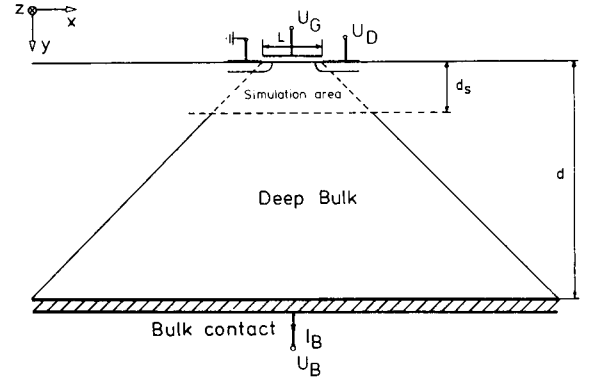


Fig. 1. The basic simulation geometry and current flow in deep bulk.

and A_n (A_p) and B_n (B_p) represent the electron (hole) ionization coefficients.

Equations (5a) and (5b) are the common Shockley-Read-Hall terms for thermal bulk and surface recombination processes. Equation (5c) describes Auger recombination as given in [5]. In (5d) we assume the validity of Chynoweth's law [6]:

$$\alpha_{n,p}(E) = A_{n,p} \exp\left(-\frac{B_{n,p}}{|\vec{E}|}\right). \quad (5e)$$

In the exponential expression of (5d) we do not use the absolute value of the electric field but only the component parallel to the current density. The field component perpendicular to the current flow does not cause ionization since the carriers only gain energy from the field component parallel to their motion.

Various authors have determined the ionization parameters A_n , A_p , B_n , B_p [7], [8]. The experimental method of van Overstraeten *et al.* [9] seems to be very reliable and our own investigations, as well as those by other authors [10], support their results.

It has to be said, however, that Chynoweth's law carries all the disadvantages of a purely phenomenological approach when compared to more theoretically founded and accurate considerations [11]. The dark space phenomenon (nonlocal effects and threshold energy effects) [12], for instance, which might be important for miniaturized devices is not at all accounted for. In spite of all its drawbacks our decision was still in favor of Chynoweth's law because no quantitative verification of more sophisticated theories has as yet been reported.

As far as modeling of other parameters (e.g., carrier mobility) is concerned, extensive treatment can be found in the literature [13].

Fig. 1 shows the simulation geometry which is implemented in our program. Current flow in deep bulk, carried by avalanche-generated holes which are repelled from the source and drain regions, causes a voltage drop across the parasitic bulk resistance. There are several options to model this effect: (a) a total three-dimensional analysis; (b) extension of the simulation over the entire bulk area; (c) extension of the two-dimensional simulation over the depletion region and using an (effective) bulk resistor. To save excessive computer resources, which would be necessary for (a), option (c) has been preferred. It allows to

account for current spread into the third dimension and, additionally, consumes less computer time than (b). Thus the voltage drop across the parasitic bulk resistance simulates a more positive bulk bias and, if large enough, is able to forward-bias the parasitic bipolar n-p-n transistor (source, bulk, and drain). This causes a larger drain current and facilitates breakdown which then will occur at smaller drain voltages. In the following we should like to suggest an easy method to estimate the value of the bulk resistor. It is taken that current spreads at an angle of 45 deg into both directions perpendicular to its flow (x - and z -direction in Fig. 1). This assumption is arbitrary but not implausible, and, furthermore, if any diffusion current is neglected, one obtains directly the following expression for the electric field in the substrate:

$$\frac{d\psi}{dy} = \frac{I_B}{\kappa A} = \frac{I_B}{\kappa(L + 2y)(W + 2y)} \quad (6)$$

with κ standing for the conductivity of the substrate and A standing for the area of the current flow. L and W are channel length and channel width, respectively. Integrating this equation along y from the end of the simulation area d_s to the bulk contact we obtain

$$R_{\text{Bulk}} = \frac{\int_{d_s}^d \frac{d\psi}{dy} dy}{I_B} = \frac{1}{2\kappa(W - L)} \left(\ln \left(\frac{L + 2d}{L + 2d_s} \right) - \ln \left(\frac{W + 2d}{W + 2d_s} \right) \right). \quad (7)$$

For $L = W$, (7) simplifies to

$$R_{\text{Bulk}} = \frac{d - d_s}{\kappa(L + 2d)(L + 2d_s)}. \quad (8)$$

This calculation is fairly crude in comparison to the elaborate solution of the basic equations. However, more precise calculations are very complicated and the present method is sufficient to investigate the influence of the parasitic bulk resistance, at least qualitatively. The influence of the bulk resistance is treated more thoroughly in [16].

III. A MODIFIED FORM OF GUMMEL'S ALGORITHM

Equations (1) and (2) represent a system of three coupled nonlinear partial differential equations which have to be solved consistently. Essentially this is accomplished by substituting the differential equations by finite difference equations which are linearized using a modified form of Gummel's algorithm [14]. Therefore, the rather expensive simultaneous solution is avoided and the high memory requirements [15] are relaxed. The design of the finite difference mesh has to be undertaken with extraordinary care to obtain a fair tradeoff between too large a discretization error and too fine a mesh. Especially in case of avalanche this becomes eminently important as the ionization rate is very sensitive (exponentially) to the electric field. An accurate calculation of the avalanche generation rate requires a much more accurate calculation of the electric field. As it is not possible to design an optimal mesh *a priori*—prior

to knowing the solution—we decided to implement a procedure which adaptively refines the difference mesh with respect to the potential, carrier, and doping distribution during the solution process.

Gummel [14] proposed to solve Poisson's equation and both continuity equations step by step and to repeat this procedure until convergence has been reached. In MOS transistors, also with moderate avalanche, there is only negligible majority carrier current flow (holes for n-channel devices) and the quasi-fermipotential for the majority carriers remains fairly constant, at least in regions with a large majority carrier density. The majority carrier density is determined mainly by the electric potential. The coupling of Poisson's equation with the continuity equation of majority carriers is extremely weak whereas it turns out to be fairly strong with the continuity equation of minority carriers, particularly if the device operates in strong inversion. Computer time can, therefore, be economized by repeatedly solving Poisson's equation and the continuity equation for minority carriers before performing one iteration of the continuity equation for majority carriers. This equation is solved only in certain cycles. If it turns out after one iteration of the majority carrier equation that changes in majority carrier density are large, potential and this density will be iterated until consistency is restored. Then the procedure restarts with the minority carrier equation again unless convergence has been reached. Thus the number of iterations is small for weak or negligible avalanche as well as for strong avalanche.

Ionization rates are recalculated in all those cycles in which the majority carrier equation is solved. Since the procedure is started without ionization, the total current will increase by a certain amount after each recalculation of the ionization rates. This increase will be approximately given by the ionization due to the excess carriers which arise from updating the carrier densities within each iteration. The current will, therefore, approximately behave like a geometric series.

Besides economizing computer time, our procedure offers the benefit of calculating only the lowest value for the current in case of an S -shaped characteristic. The advantage lies in the fact that the procedure will always lead to a stable operating point and will never enter the unstable negative resistance region. Only if drain voltage is beyond breakdown, the geometric series will not converge resulting in infinite current which is in trivial consistence with experiment.

IV. EXPLANATION OF THE BREAKDOWN VOLTAGE AND THE SNAP-BACK EFFECT

In this chapter we should like to present calculations for a 1- μm gate length n-channel MOS transistor. The lateral subdiffusion and the junction depth of the source and drain regions are 0.2 and 0.3 μm , respectively. A deep channel implantation with fairly high dose was supposed to have been performed in order to suppress punchthrough.

Fig. 2 shows calculated drain and bulk currents versus drain voltage for that transistor. For $V_{GS} = 1\text{ V}$ breakdown is reached at $V_{DS} = 5.6\text{ V}$ whereas 8.4 V are necessary to lead the device into breakdown if no gate voltage is applied. On first glance that seems to be paradox, if one considers that $V_{GS} = 0\text{ V}$ causes larger peak values of the electric field. The

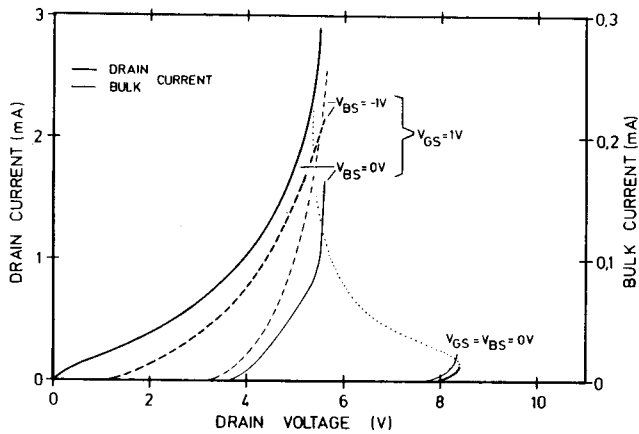


Fig. 2. Drain (thick lines) and bulk (thin) current characteristics of the analyzed transistor.

explanation of this phenomenon lies in the low current level. First let us discuss the $V_{GS} = 0$ V characteristic:

Although the probability of ionization is larger than for $V_{GS} = 1$ V, the generation rate still remains small as there is little current flow causing ionization. With increasing drain voltage the drain current and, consequently, avalanche generation as well as hole density increase. This additional space charge even lowers the potential barrier between source and bulk as will be demonstrated later. Now an internal feedback mechanism exists which acts as follows: because of the lower potential barrier the electron current injected by source, and consequently, the avalanche generation increase. Thus the hole density rises even more and, in turn, further lowers the potential barrier. Once the feedback gain becomes unity the node currents rise unlimited unless controlled by external resistors in the current paths. Furthermore, owing to the higher current level, the situation now becomes more and more similar to the situation at larger gate voltages. The I - V characteristic, therefore, has to move towards the $V_{GS} = 1$ V characteristic and the drain voltage decreases with increasing drain current. This effect implies negative resistance and is usually called "snap-back." The voltage drop of the hole current at the parasitic resistor of the deep bulk also lowers the potential barrier and thus enhances the feedback gain.

A more transparent description of the negative resistance phenomenon can be given too: the voltage drop of the hole current at the parasitic bulk resistor must not be larger than the applied negative bulk bias plus the source-to-bulk built-in potential unless the source-to-bulk junction will be biased in the forward direction. Thus the hole current is limited for given R_{Bulk} . If the drain voltage—starting at fairly low values—is increased, the avalanche generation rate will increase as long as the bulk current reaches its critical value. Of course, a further increase in drain voltage is impossible as the slope of the I - V characteristic is vertical at this point. However, with increasing drain current, even with constant V_{DS} , the avalanche generation according to (5d) would increase what should not at all occur. The only chance to keep avalanche generation constant is to decrease V_{DS} with increasing drain current.

Applying a negative bulk voltage renders breakdown more

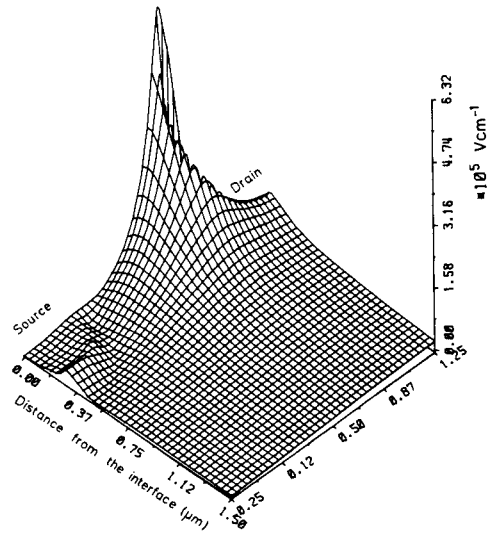


Fig. 3. Electric field distribution ($V_{GS} = 0$ V, $V_{DS} = 8$ V, $V_{BS} = 0$ V).

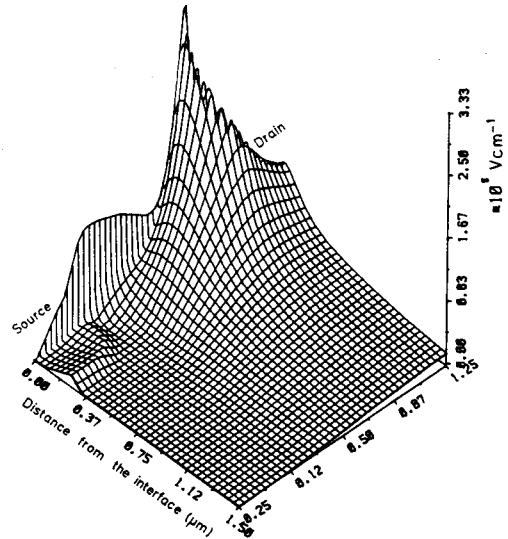


Fig. 4. Electric field distribution ($V_{GS} = 2$ V, $V_{DS} = 5.6$ V, $V_{BS} = 0$ V).

difficult although it increases the bulk current level. The reason for this phenomenon lies in the hole density which is decreased by applying a more negative bulk bias which, in turn, attracts the holes.

There exists an additional feedback mechanism apart from the one just mentioned: the carriers generated by ionization cause again ionization. This effect leads to an "avalanche-like" increase of both carrier densities, and determines the breakdown voltage of a p-n junction. The feedback depends on the ionization ability of both carrier types and is of little importance in our case. For MOS transistors the mechanism described above is much stronger and is active with even vanishing ionization ability of holes.

In the following we should like to discuss internal physical quantities at $V_{GS} = 0$ V, $V_{DS} = 8$ V, and $V_{GS} = 2$ V, $V_{DS} = 5.6$ V, respectively. These operating points have been chosen to explain clearly the physical phenomena which eventually lead to the snap-back effect. The computed drain currents

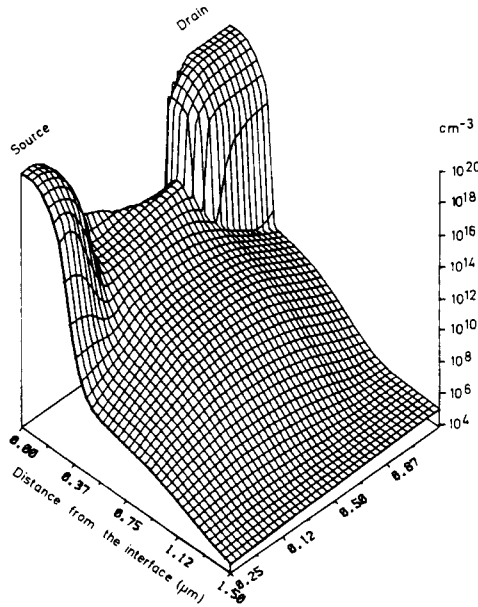


Fig. 5. Electron density distribution ($V_{GS} = 0$ V, $V_{DS} = 8$ V, $V_{BS} = 0$ V).

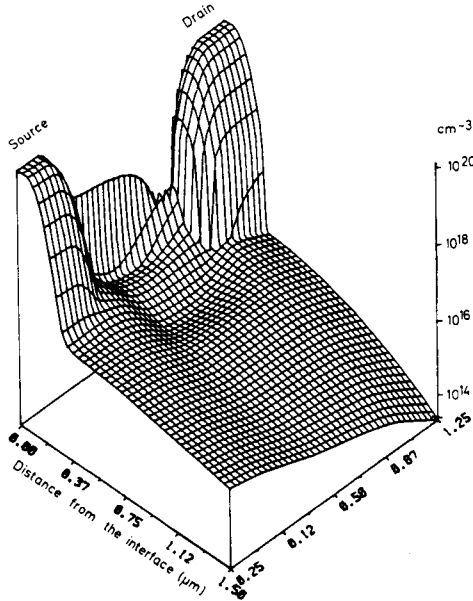


Fig. 6. Electron density distribution ($V_{GS} = 2$ V, $V_{DS} = 5.6$ V, $V_{BS} = 0$ V).

are about 20 μ A and 15 mA, respectively. Since the $V_{GS} = 2$ V characteristic were out of locus bounds, it is not drawn in Fig. 2.

Fig. 3 shows the distribution of the electric field at the first operating point; Fig. 4 at the second. As already outlined above, the peak value of the electric field for the first operating point is about twice as large as it is for the second. The substantial gate-induced field is nicely visible in the channel region of Fig. 4. Comparing both figures one finds the source to bulk barrier in Fig. 4 only to be half as large as in Fig. 3 (watch the different scale). This is due to the influence of the hole density on electric potential. When looking at Fig. 3 one notices a slight but not yet critical onset of punchthrough. The protrusion of the electric field towards the source region

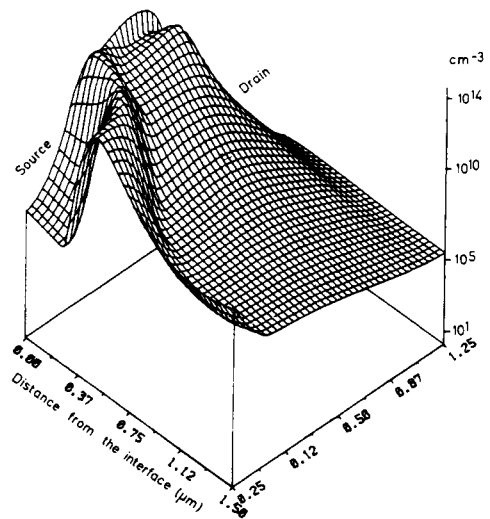


Fig. 7. Hole density distribution ($V_{GS} = 0$ V, $V_{DS} = 8$ V, $V_{BS} = 0$ V).

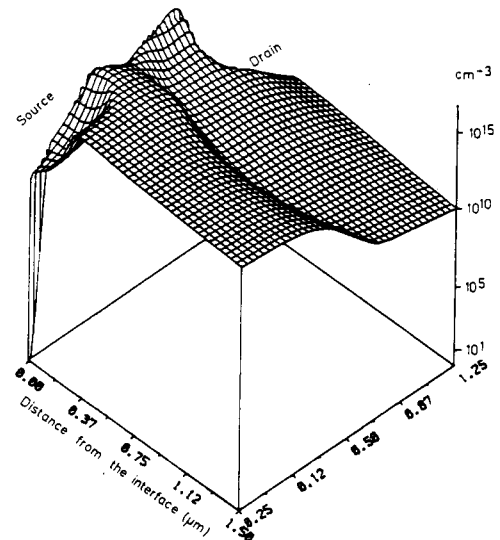


Fig. 8. Hole density distribution ($V_{GS} = 2$ V, $V_{DS} = 5.6$ V, $V_{BS} = 0$ V).

is no longer restrained to the channel region near the interface but deviates slightly into the bulk. When it eventually reaches the source region (typically for even higher V_{DS}), the thus created current path effects punchthrough. No indication of punchthrough exists at $V_{DS} = 5.6$ V, though.

Figs. 5 and 6 show the electron distribution for both operating points in a logarithmic scale. At the first operating point, Fig. 5, the transistor is turned off; there is no inversion layer between the source and drain regions which can be found, as expected, in Fig. 6 at the second operating point. It should be noted that in Fig. 6 the electron density does not drop below the intrinsic number in contrast to Fig. 5. The reason for this can be found in source barrier lowering brought about by the increased hole density as will become clear with the next figures.

The corresponding hole densities are given in Figs. 7 and 8, respectively. One should bear in mind that all the holes outside the undisturbed bulk region are generated by impact ionization. In agreement with the electron densities the hole density is also much larger for $V_{GS} = 2$ V. The large hole density near the

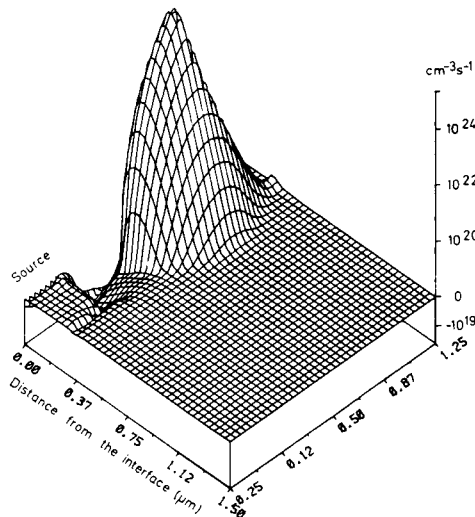


Fig. 9. Generation/recombination rate ($V_{GS} = 0$ V, $V_{DS} = 8$ V, $V_{BS} = 0$ V).

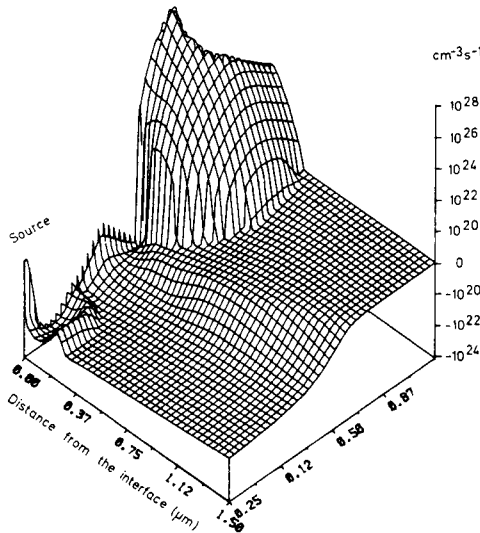


Fig. 10. Generation/recombination rate ($V_{GS} = 2$ V, $V_{DS} = 5.6$ V, $V_{BS} = 0$ V).

source partially compensates the acceptor doping. Thus the potential barrier at the source is lowered and high electron injection from the source region ensues. So far we have explained the situation at breakdown and described the process which leads to the negative resistance. However, the question arises whether or not the negative resistance will always dominate in the avalanche region.

V. DISCUSSION OF THE SUSTAIN VOLTAGE

Looking at Fig. 5 again, we find that the negative resistance branch of the $V_{GS} = 0$ V characteristic for large current levels leads into a vertical slope, i.e., the decrease of V_{DS} is stopped. The corresponding drain voltage is called "sustain voltage"; it increases weakly with increasing V_{GS} because a large gate bias smoothes the electric field distribution thus lowering its peak value. The existence of a nearly unique sustain voltage can be explained by heavy recombination as the following figures will demonstrate.

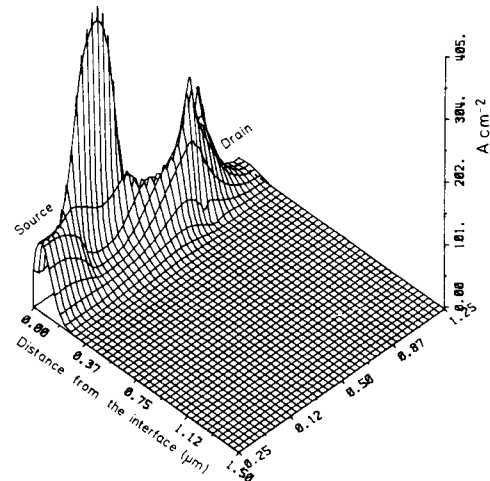


Fig. 11. Electron current density ($V_{GS} = 0$ V, $V_{DS} = 8$ V, $V_{BS} = 0$ V).

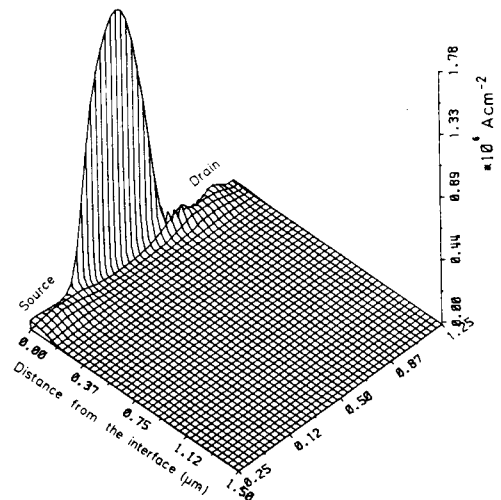
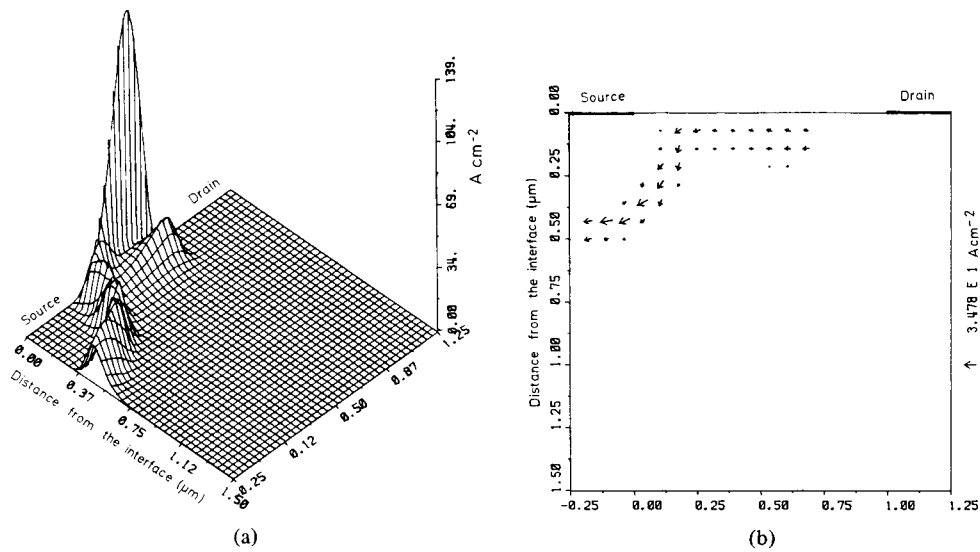
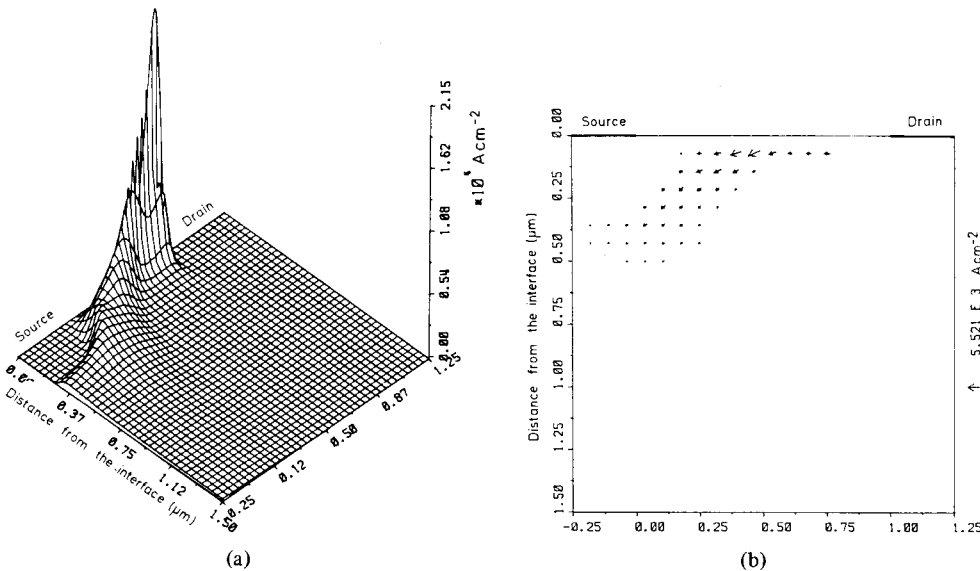


Fig. 12. Electron current density ($V_{GS} = 2$ V, $V_{DS} = 5.6$ V, $V_{BS} = 0$ V).

Figs. 9 and 10 show the generation/recombination rate in a quasi-logarithmic scale for the same operating points are discussed in the last chapter. First the 0 gate voltage operating point, Fig. 9, is scrutinized.

In the pinch-off region the large electric field (refer to Fig. 3) causes heavy impact ionization. It consists of the product of the local (mainly electron) current density and the ionization probability (equation (5d)). The heavy ionization does not extend into the drain region itself as the electric field is almost extinguished by the high doping level. Between source and pinch-off region some recombination occurs since the carrier density product there (Figs. 5 and 7) is rather large. As the magnitude of the carrier densities is far below 10^{19} thermal (Shockley-Read-Hall) recombination prevails. No visible recombination, however, takes place in the source region directly but at the junction where the densities of both carrier types are equal and maximize (5a). The positive peak value (generation) of this distribution nearly reaches 10^{26} pairs per cm^3 and second. Its negative peak values (recombination) are at some 10^{19} .

In contrast, in Fig. 10 the avalanche generation rate is increased by about two orders of magnitude, due to the larger

Fig. 13. Hole current density ($V_{GS} = 0 \text{ V}$, $V_{DS} = 8 \text{ V}$, $V_{BS} = 0 \text{ V}$).Fig. 14. Hole current density ($V_{GS} = 2 \text{ V}$, $V_{DS} = 5.6 \text{ V}$, $V_{BS} = 0 \text{ V}$).

electron current—the device now operates in strong inversion. However, the carrier densities are also increased which enables recombination to become more dominant. Recombination is now active in about half of the presented area and raised by about 5 orders of magnitude. In the source region even Auger recombination occurs. For a given carrier density product this kind of recombination is the larger the more different the carrier densities are (equation (5c)). The source-to-bulk junction indicates the turnover from the Auger to the SRH process. Recombination now consumes a considerable part of the avalanche generated holes and at first glance we can say that any increase in avalanche generation will be compensated by recombination via larger carrier densities. From that point of view the demand for a constant generation rate will no longer exist and the decrease of the drain voltage is stopped. Thus the sustain voltage results.

Snap-back voltage decreases with increasing gate voltage whereas the opposite is true for the sustain voltage. At large cur-

rent levels—due to large gate voltage and/or short channel—snap-back voltage might become smaller than the sustain voltage. In that situation heavy recombination sets on before the hole density has increased enough to initiate snap-back. Thus the negative resistance phenomenon vanishes in those applications.

Various calculations using different values for the carrier lifetimes have shown a slight increase in sustain voltage with decreasing carrier lifetimes. Although recombination plays an important role in the description of that important feature, it is not possible to increase markedly the sustain voltage by lifetime doping. An increase in sustain voltage would raise the electric field which is already prominent. Therefore, the additional amount of ionization would almost compensate the shift of the sustain voltage.

The distribution of the absolute value of the electron current density is given in Figs. 11 and 12. There is a difference of about four orders of magnitude in its peak value. In both figures one can see the current spreading in the pinch-off region which

forces the current to flatten and extend over a larger area at the same time before it reaches the drain region. Noticeable is the actual "current sheet" at the interface in Fig. 12.

Figs. 13 and 14 show the absolute value of the hole current density. The plots at the right-hand sides show the direction of the hole current. For the first operating point a current peak value of about 140 A/cm^2 occurs which is almost one-third of the peak value of the corresponding electron current density (Fig. 11). The source of the hole current resides in the pinch-off region; current flows along the interface and then bypasses the source junction. Owing to the deep channel implantation, the conductivity below the source is high and the hole current remains mainly there. It is to note that current flow does not vanish below the source since recombination is weak for this operating point (cf., Figs. 5, 7, 9). In the other operating point the numerical value of the hole current density has increased by a factor of 150, owing to the larger avalanche generation. Qualitatively the tenor of this figure is the same as in the last one; below the source junction, however, the hole current is diminished by recombination (cf., Figs. 6, 8, 10).

The $1\text{-}\mu\text{m}$ transistor which we have analyzed in this contribution has not yet been fabricated. Particularly for devices in the development stage, numerical analysis is of paramount importance. Comparisons with experiment, which quantitatively verify the applicability of our model, for a transistor with a longer channel can be found in [16].

VI. CONCLUSION

In this contribution we have given a numerical method to analyze the avalanche effect in MOS transistors. Our model is based on the consistent solution of the basic semiconductor equations. In this way reliable values for the node currents can be calculated. The main power of our algorithm, however, lies in the prediction of the internal quantities which allow better principal understanding of breakdown phenomena. The hole density is shown to play an important role in the mechanism of breakdown effects. The voltage drop of the bulk current at the parasitic resistance of the deep bulk causes an internal feedback phenomenon similar to the base resistance in bipolar transistor breakdown. A negative resistance branch of the characteristic can thus arise which is usually referred to as snap back. High currents owing to high gate voltage and/or short channel length and the resulting strong recombination tend to cover the snap back effect. Owing to the lack of space and to avoid confusion only results for an n-channel transistor have been presented. However, p-channel devices can be analyzed in a similar manner.

Our computer program MINIMOS is available for just the handling costs.

ACKNOWLEDGMENT

The authors gratefully acknowledge the essential help in providing MOS devices by Siemens AG Munich and thank Dr. F. H. Gänsslen, IBM J. Watson Research Laboratory, Yorktown Heights, NY, for valuable advice including unpublished results. Critical reading of the manuscript by Dr. J. Machek is greatly appreciated. A generous amount of computer time has been provided by the "Interuniversitäres Rechenzentrum der

Technischen Universität Wien." The authors would like to thank the reviewers of this paper for helpful comments and suggestions.

REFERENCES

- [1] S. Selberherr, A. Schütz, and H. W. Pötzl, "MINIMOS—A two dimensional MOS transistor analyser," *IEEE Trans. Electron Devices*, vol. ED-27, pp. 1540–1550, Aug. 1980.
- [2] T. Toyabe, K. Yamaguchi, S. Asai, and M. S. Mock, "A numerical model of avalanche breakdown in MOSFET's," *IEEE Trans. Electron Devices*, vol. ED-25, pp. 825–832, July 1978.
- [3] M. S. Mock, "A two dimensional mathematical model of the insulated gate field effect transistor," *Solid-State Electron.*, vol. SSE-16, pp. 601–609, 1973.
- [4] W. V. van Roosbroeck, "Theory of flow of electrons and holes in Germanium and other semiconductors," *Bell Syst. Tech. J.*, vol. 29, pp. 560–607, 1950.
- [5] D. C. d'Avanzo, "Modeling and characterization of short-channel double diffused MOS transistors," Stanford Univ. Tech. Rep. G-201-6, 1980.
- [6] A. G. Chynoweth, "Ionization rates for electrons and holes in silicon," *Phys. Rev.*, vol. 109, pp. 1537–1540, 1958.
- [7] C. A. Lee, R. A. Logan, R. L. Batdorf, J. J. Kleimack, and W. Wiegmann, "Ionization rates of holes and electrons in silicon," *Phys. Rev.*, vol. 134, pp. A761–773, 1964.
- [8] J. L. Moll and R. van Overstraeten, "Charge multiplication in silicon p-n junctions," *Solid-State Electron.*, vol. SSE-6, pp. 147–157, 1963.
- [9] R. van Overstraeten and H. de Man, "Measurement of the ionization rates in diffused silicon p-n junctions," *Solid State Electron.*, SSE-13, pp. 583–608, 1970.
- [10] V. A. K. Temple and M. S. Adler, "Calculation of diffusion curvature related avalanche breakdown in high-voltage planar p-n junctions," *IEEE Trans. Electron Devices*, vol. ED-22, pp. 910–916, Oct. 1975.
- [11] G. A. Baraff, "Distribution functions and ionization rates for hot electrons in semiconductors," *Phys. Rev.*, vol. 128, pp. 2507–2517, 1962.
- [12] Y. Okuto and C. R. Crowell, "Threshold energy effect on avalanche breakdown voltage in semiconductor junctions," *Solid State Electron.*, vol. SSE-18, pp. 161–168, 1975.
- [13] S. Selberherr, "Zweidimensionale Modellierung von MOS-Transistoren," Ph.D. dissertation, TU Wien, 1981.
- [14] H. K. Gummel, "A self consistent iterative scheme for one dimensional steady state transistor calculations," *IEEE Trans. Electron Devices*, vol. ED-11, pp. 455–465, 1964.
- [15] P. E. Cottrell and E. M. Buturla, "Two dimensional static and transient simulation of mobile carrier transport in a semiconductor," in *Proc. NASECODE I Conf.*, pp. 31–64, Dublin, Ireland, 1979.
- [16] A. Schütz, S. Selberherr, and H. W. Pötzl, "A two-dimensional model of the avalanche effect in MOS-Transistors," *Solid State Electronics*, to be published.

*



Alfred Schütz (M'80) was born in Linz, Austria, in 1955. He received the Diplomingenieur degree in communications from the Technical University of Vienna in 1978.

In 1979 he joined the Institut für Allgemeine Elektrotechnik und Elektronik, previously called the Institut für Physikalische Elektronik, at the Technical University of Vienna as an Assistant Professor. Since that time he works on modeling of semiconductor devices.



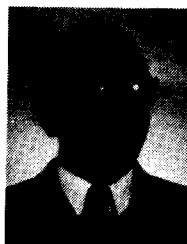
Siegfried Selberherr (M'79) was born in Klosterneuburg, Austria, on August 3, 1955. He received the Diplomingenieur degree in control theory and industrial electronics from the Technical University of Vienna in 1978.

Since that time he has joined the Institut für Allgemeine Elektrotechnik und Elektronik, previously called the Institut für Physikalische Elektronik, at the Technical University of Vienna as an Assistant Professor. He finished his thesis in 1981. His current topics are model-

ing and simulation of devices and circuits for application in electronic systems.

He is a member of the Association for Computing Machinery in 1979 and the Society of Industrial and Applied Mathematics in 1980.

*



Hans W. Pötzl (M'62) was born in Vienna, Austria, in 1930. He received the Ph.D. degree in mathematics from the University of Vienna in 1952 and the degree of "Diplomingenieur" from the Technical University Vienna in 1956.

In 1957 he joined the Institute for High Frequency Techniques, and worked under the supervision of Prof. König in the fields of noise and propagation modes in electron beams. In 1964 he became "Dozent." In 1966 the chair of Prof. Rothe, University of Technology,

Karlsruhe, BRD, was offered to him. However, he decided to stay at the Technical University Vienna as Full Professor in Physical Electronics. Since 1966 he works in the semiconductor field investigating hot electrons, heliconwaves, the acousto-electric effect, cyclotron radiation from semiconductors in the far infrared region and diffusion in impatt diodes. Since 1977 he works on transistor modeling. He is coauthor of a book and author or coauthor of 40 journal articles.

He is member of the Austrian Academy of Science. In 1975 he received the award "Technikpreis der Wiener Wirtschaft."